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A real option model for renewable energy policy evaluation with application to solar PV power generation in China

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ABSTRACT

This study proposes a policy evaluation model from the perspective of government and investors. The proposed model, which integrates American option method and two-factor learning curve method, can be used to evaluate the unit decision value and save-path rate for renewable energy development and examine the existence of balance point of interest. Several uncertain factors including non-renewable energy cost, carbon price, renewable energy cost, and price subsidy are all considered in this model. The model has been applied to evaluate the solar photovoltaic (PV) power generation in China. Our empirical results show that real option analysis (ROA) is more effective than net present value analysis (NPV) when handling uncertainty. Under current level of subsidy, the government would suffer loss and the investors could benefit so that it is difficult to achieve the balance of interest during the planning period. With the reduction of subsidy rate, they can achieve the balance of interest.

Contents

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1. Introduction

When energy shortage and environmental issues increasingly become the bottleneck restricting the social and economic development, more and more countries take steps to develop renewable energy. The development of renewable energy in the world shows a increasing trend. In 2012, the global renewable energy investment reached 24.4 billion dollars. However, the promotion of renewable energy is affected by its dispersion and instability which will result in high research & development (R&D) cost, difficulty of investment recovery, long and deferred planning processes, and high investment risks. Therefore, supportive policies and statutes are essential. Currently, a lot of policies like feed-in tariff (FIT), renewable portfolio standard (RPS), and tax rebates have been formulated and implemented to promote the use of renewable energy in the world.

China as a big country of energy production and consumption in the world faces more serve situation of increasing energy supply. China has great potential to develop renewable energy and has made great progress after years of promotion. To lower investment costs and attract more investments, Chinese government has implemented some policies, like equipment investment subsidy, tax relief and FIT. Supported by these policies, Chinese government also made a series of development plan for renewable energy. The Middle and Long Term Programme of Renewable Energy Development states that renewable energy should reach more than 15% of the total energy consumption in 2020. Regarding solar PV, the Opinions of State Council on Promoting the Healthy Development of the PV Industry proposed the installed capacity of solar PV power generation reach 35,000 MW and above by 2015. The 12th Five-year Plan of Chinese renewable energy also posed that installed capacity of solar PV reach 50,000 MW by 2020. Under current development plan, whether the current level of subsidy is favorable for government and investors as well as what is the appropriate level of subsidy are worthy of attention.

Some scholars [1–3] have established model to evaluate the policy benefit of developing renewable energy for government. The factors they considered contains non-renewable energy (NRE) cost, renewable energy cost, and carbon mitigation cost. However, most of the studies did not consider the benefits of both government and investors, whereas policy evaluation considering the benefit of government and investors seems to be more meaningful. In addition, some studies just only considered the economic value and concluded that government has always been at a loss. These are inappropriate. The value of developing renewable energy means not only the economic benefit but a kind of comprehensive benefit. This paper proposes a renewable energy policy evaluation model that integrates the American opinion and two-factor learning curve. The uncertain NRE cost, carbon price, renewable energy cost, and price subsidy are all considered. According to this model, we can derive the unit decision value and save-path rate for government and investors during the planning period. The existence of the balance point of interest can also be examined, based on which the applicability and effectiveness of policy can be assessed.

The remainder of this paper is organized as follows: Section 2 provides a literature review. Section 3 describes methodology which contains the factors involved in analysis and the real option model. Section 4 presents the empirical analysis including parameter estimation and scenario analysis. Section 5 concludes the study.

2. Literature review

2.1. The real option theory

Due to its characteristic of time-consuming, large scale and high cost, the development of renewable energy is constrained by high investment risks and uncertainty. The uncertainties lie in volatility of energy price and the speed of technological progress. Recently, the disadvantages of traditional techniques including NPV and discounted cash flow approaches (DCF) proposed by Fisher [4,5] are increasingly recognized [6–8]. Real option is an effective tool on resolving uncertainty. Real option could effectively analyze the investment opportunities combining the present and the future. If real option approach is used to assess the benefit of renewable energy development policies, managerial flexibility neglected by traditional assessment methods can be quantified. The possibility of underestimating policy value can also be minimized [9]. Therefore, real option is more and more used in renewable energy investment and policy evaluation.

Real option was originally developed in the 1970s by Black and Scholes [10] and Merton [11] to evaluate financial options. Myers [12] found their similarities and applied the option pricing methods to determine the value of physical assets firstly. He called it real option. After that, some scholars proposed a few basic concepts about real option. Trigeorigis and Mason [13] referred to the investment value of an options value with managerial flexibility obtained as "expanded" or "strategic" NPV. This value is the sum of the traditional NPV and managerial flexibility value. Sarkar [14] indicates that the increase of uncertainty could raise the probability of investment in a given environment. Copeland and Antikarov [15] established a unified model based on real option and put forward five solving steps which could be used to option evaluation and project valuation. They thought option was one important part of expected value of project in future.

For the numerical solution method of real option, Cox et al. [16] proposed the binomial model and its extension based on dynamic programming approach. Brennan and Schwartz [17], Majd and Pindyck [18] used partial differential equation to solve their option pricing models. The method used by Boyle [19] was Monte Carlo simulation. He [20] also demonstrated how to deal with the situation of two random variables. Longstaff and Schwartz [21] proposed Least Squares Monte Carlo method (LSM) which is one kind of American option solving method based on Monte Carlo simulation and least squares.

2.2. Application of real option to renewable energy investment

A number of studies focused on the area of renewable energy investment. Venetsanos et al. [22] analyzed the impact of uncertain factors on renewable energy investment and how to choose optimal investment time. The factors considered in their study contain fuel price, environmental regulations, initial capital investment, technology, and market structure. Davis and Owens [23] developed a real option model which uses a binomial lattice structure. The authors argued that a binomial lattice reveals the economic intuition underlying the decision-making process, while a numerical example illustrates the option components embedded in a simplified representation of current US Federal renewable energy research, development, demonstration and deployment. By analyzing the option value of power plant, Kiriyama and Suzuki [24] thought, with the arrival of carbon emission limiting age, nuclear power would become more and more important. Gollier et al. [25] compared the one-time investment of large nuclear power project and flexibly sequential investment of small nuclear power project with application of real option and considering uncertain electricity price. Yu et al. [26] focused on evaluating the flexibilities associated with switching tariff in Spanish electricity markets. Using the real options framework, they implemented numerical techniques to evaluate switching tariff for different wind generation assets, and identified optimal switching policies and values. Siddiqui et al. [27] examined the strategy for renewable energy R&D in the United States. Kjaerland [28] applied real

option evaluation framework of Dixit and Pindyck [6] to potential hydropower investments in Norway. He quantified the option value and analyzed the timing and aggregate investment behavior in this industry. His study took into account the uncertainty of fossil fuel price, water reserves, risk-free interest rate, investment cost, variable cost, and the best investment time. Fuss [29] mainly analyzed the impact of uncertainties on power sector. They emphasized the market uncertainty, the fluctuation of CO_2 price, and the policy uncertainty. Bockman et al. [30] developed a real options-based method with continuous scaling for assessing small hydropower projects. Munoz et al. [31] presented a decision-making tool for investment in wind energy plant using a real option approach. To illustrate their decision-making method which allows wind energy investment and to decide whether to invest under different scenarios, they performed several realistic case studies. Siddiqui and Fleten [32] examined how a staged commercialization program for an unconventional energy technology could proceed under uncertainty. Martinez Cesena and Mutale [33] proposed an advanced real option methodology for renewable energy generation projects planning, and illustrated the methodology using variations of a hydropower case study. Their results showed higher expected profits for projects planned with the advanced real option methodology compared with other methods.

2.3. Application of real option to policy evaluation of renewable energy

Under current situation, the development of renewable energy cannot run normally without the support of policy. So lots of authors have directed attention to the policy evaluation of renewable energy using real option theory. Chorister and Robert [34] applied real option methods to determine the implementation time and value of environmental policy. Yang et al. [35] used a multi-stage dynamic programming model to analyze the impact of governmental climate policy uncertainty on coal-fired power stations, gas stations and nuclear power stations, and they finally estimated the risks caused by the uncertain carbon price and energy price. The results showed that real option is an effective tool to quantify the effect of climate policy uncertainty on power plant investment. Kumbaroglu et al. [36] analyzed renewable energy projects in Turkey and proposed the popularity of renewable energy is highly affected by liberalized electricity market uncertainty and the investors' estimation to uncertainty. Scatasta and Tim [37] analyzed the success of renewable energy certificate trading and FIT on promoting investments in wind projects. The results showed that the certificates may be the most effective policy to motivate investment in wind projects. Herve-Mignucci [38] presented a real option method to study the effects of carbon price uncertainty reductions and carbon price caps on new investments in different types of energy generation plan (EGP). The results suggested that well defined caps are better suited to promote investment in low carbon energy generation plan and renewable energy plan (REP). Lee and Shih [1] presented a policy benefit evaluation model that integrates cost efficiency curve information on renewable power generation technologies into real options analysis methods. The proposed model could be used to evaluate the policy value provided by developing renewable energy in face of uncertain fossil fuel price and renewable energy policy-related factors. At the end of the paper, an example of wind power in Taiwan was analyzed. The results proved real option could be a good tool of quantifying the uncertainties in renewable energy planning. The value of Taiwan's wind power development policy planning could also be obtained. The sensitivity analysis of FIT and internalization of external costs proved the internalization of external costs is a good supportive policy. And the appropriate FIT level are also obtained. Lee and Shih [2] also examined the relationship between implementation flexibility and strategic value of wind power development strategy. They proposed a policy evaluation model from the perspective of government. The model was based on real option methods. The results provided a good reference for the precise evaluation of government policies and the formation of renewable energy policy. Boomsma et al. [39] adopted a real option approach to analyze investment timing and capacity choice for renewable energy projects under the most extensively employed policy schemes, namely, FIT and renewable energy certificate trading. Restricting attention to Norway in a case study based on wind power, the authors found that the FIT encourages earlier investment. Nevertheless, as investment has been undertaken, renewable energy certificate trading creates incentives for larger projects. Reuter et al. [40] proposed an analytical framework which was used to analyze the decision of electricity production investment, technology choice, and optimized operation. The electricity price uncertainty, market uncertainty and policy uncertainty were all considered in this framework. This framework could be used to evaluate energy policies and examine the reaction of investor to uncertainty. Authors took Germany as an example to carry out an empirical analysis. The results proved FIT was an useful tool to promote renewable energy investment, and the level of FIT in Germany was close to optimal. Reuter et al. [41] also prosed an real option model to evaluate investment in wind power and pumped storage. They used it to analyze the situation in Germany and Norway. The author explained in detail the impact of changes in electricity prices, increase in new energy scale, the uncertainties resulting from intermittent wind load fluctuations, and investment subsidy policy. Lin and Wesseh Jr. [3] estimated the value of solar PV power generation under fossil energy price uncertainty, technical learning effect, and FIT. The author believed FIT would be a good policy in future and the internalization of external costs could raise option value. The current level of FIT was not optimal. It should be raised to between 1.58 and 1.7 yuan/kWh. Manuel and Jose [42] discussed the influence of policy support mechanism on renewable energy investment with uncertain initial investment cost and production cost. They used the real option and Monte Carlo simulation method. The result using these two different methods was similar. And Finland's support for renewable energy was the most favorable, Denmark and Poland followed.

In sum, these studies further demonstrated that the real options evaluation model is appropriate for evaluating the value of developing renewable energy and examining the influences of related policies. Previous studies mainly analyzed the execution time and the implication of policies in the case of NRE cost uncertainty, carbon emission cost uncertainty and other uncertainties from one perspective i.e., government or investors. These studies are valuable. However, there is a lack of the analysis considering the benefit of government and investors. Hence this paper steps into this gap by attempting to implement policy evaluation from the perspective of government and investors.

3. Methodology

Both government and investors are beneficiary of policy. Government is the policy maker and investors are the policy observer. The policy evaluation should consider the interests of both sides. It is meaningful to compare the effect of the subsidy on government and investors. Determining the unit decision value within the real option is to estimate unit cash flows of developing renewable energy in the future [23]. Estimating the save-path rate in different years is to calculate the proportion of the decision nodes where the unit decision value is greater than zero. Given

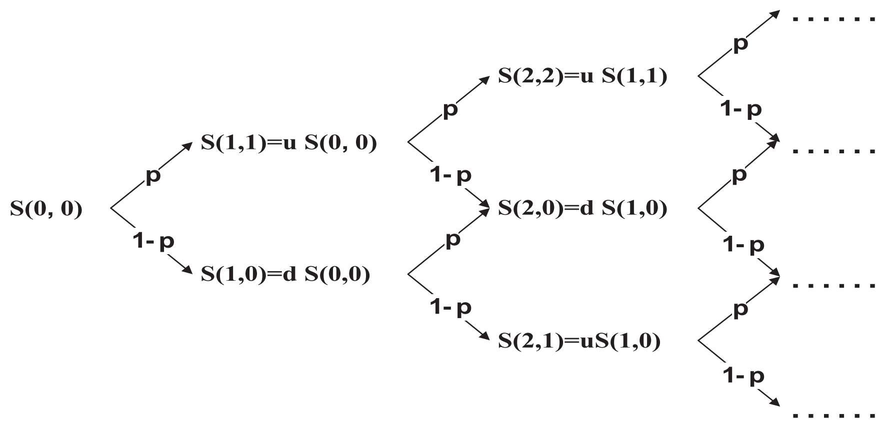

Fig. 1. Binomial lattice stochastic process of NRE cost.

above, we establish the real option model from the perspective of government and investors respectively. According to this model, the applicability of the current subsidy for government and investor are judged. The existence of interest balance point will also be examined at last (The balance point of interest is one situation where both government and investors all could benefit.).

3.1. Factors considered in policy evaluation

Renewable energy investment and policy making process are affected by many factors. This study considers four kinds of factors including NRE costs, carbon price, renewable energy cost and price subsidy for renewable energy.

3.1.1. Non-renewable energy cost

NRE cost is one of the key factors influencing the development of renewable energy, while it is mainly refers to thermal power cost in China. Volatility of NRE cost determines the pace of the development of renewable energy. When NRE cost is high, the renewable energy investment will become more attractive, when NRE cost is low, the renewable energy investment will become less attractive.

This study assumes that NRE cost follows Geometric Brown Motion (GBM) in which the uncertainty of NRE cost can be represented by two possible outcomes at each step, i.e., either increase or decrease. Zhu and Fan [43] supported this hypothesis. Hence, for an initial NRE cost represented by$S(0,0)$, the cost for the next period is stochastic and can be valued in two ways: (Fig. 1 describes binomial lattice stochastic process of NRE cost)

$$\begin{cases} S(1,1) = uS(0,0), & \text{with probability is } p \\ S(1,0) = dS(0,0), & \text{with probability is } 1-p \end{cases}$$

Generally

$$\begin{cases} S(t+1,\ i+1) = uS(t,\ i), & \text{with probability is } p, \quad 0 \le t \le T,\ \ 0 \le i \le t \\ S(t+1,\ i) = dS(t,\ i), & \text{with probability is } 1-p, \quad 0 \le t \le T,\ \ 0 \le i \le t \end{cases}$$

where $S(t,\ i)$ is NRE cost with t periods elapsed and i upward cost movement, T is the number of time periods, σ[1] is the volatility rate of NRE cost, n is the number of volatility periods, r is the risk-free interest rate, u is the range of NRE cost upward movement, $u = e^{\sigma\sqrt{T/n}}$, d is the range of NRE cost downward movement, $d = 1/u$, p is the probability of a NRE cost increase, $p = (e^{r(T/n)} - d)/(u-d)$.

3.1.2. Carbon price

In the international market, the Clean Development Mechanism (CDM) under the framework of "Kyoto Protocol" provides a good platform for carbon emissions trading between the developing countries and developed countries. According to the United Nations Environment Programme, the number of CDM projects in China rank first and account for 43% in the world. Hence, in this context, this study assumes CDM is effective. Of course, it is an ideal situation. Changes of carbon price are random. Stochastic processes can better reflect the volatility and trend of carbon price. Previous studies assumed that carbon price follow GBM [29,41,44,45]. This study supports this hypothesis. The change of carbon price is as follows (Fig. 2 describes binomial lattice stochastic process of carbon price):

$$\begin{cases} Cp(1,1) = u'Cp(0,\ 0), & \text{with probability is } q \\ Cp(1,0) = d'Cp(0,\ 0), & \text{with probability is } 1-q \end{cases}$$

Generally

$$\begin{cases} Cp(t+1,\ j+1) = u'Cp(t,\ j), & \text{with probability is } q, \quad 0 \le t \le T,\ \ 0 \le j \le t \\ Cp(t+1,\ j) = d'Cp(t,\ j), & \text{with probability is } 1-q, \quad 0 \le t \le T,\ \ 0 \le j \le t \end{cases}$$

where $Cp(t,j)$ is the carbon price with t periods elapsed and j upward cost movement, T is the number of time periods, σ'[2] is the volatility rate of carbon price, n is the number of volatility periods, u' is the range of carbon price upward movement, $u' = e^{\sigma'\sqrt{T/n}}$, d' is the range of carbon price downward movement, $d' = 1/u'$, q is the probability of a carbon price increase, $q = (e^{r(T/n)} - d')/(u' - d')$.

3.1.3. Renewable energy cost

The concept of learning curve is proposed by Wright [46]. Learning curve describes the relation between the cost and accumulation of some indexes. A lot of previous studies assumed the development of PV power generation, wind power generation, and other new energy industry are in line with the learning curve model [47–49]. Recent studies [50–53] suggested that, besides considering the use of accumulated production to calculate cost reduction, other factors that affect the rate of cost reduction, such as premium level, scale of economies, land costs, wages and interest rates, should also be considered in the cost efficiency

[1] The process of estimating $\sigma$is as follows: At first, according to historical data, we should calculate: $\mu_t = In(S_t/S_{t-1})$, $(t = 1,\ 2,\ 3,\ ....,\ l)$; Secondly, we should estimate the standard deviation rate: $S = \sqrt{(1/l-1)\sum_{t=1}^{l}(u_t - \overline{u})^2}$ or $S = \sqrt{(1/l-1)\sum_{t=1}^{l}{u_t}^2 - (1/l-1)(\sum_{t=1}^{l}u_t)^2}$; At last, volatility rate can be obtained: $\sigma = S/\sqrt{\Delta t}$, where: $l+1$ is the number of observation, S_i is the NRE cost at the end of one year, Δt is the length of time interval with the year as the unit.

[2] The method of estimating σ' is the same as the method of estimating σ.

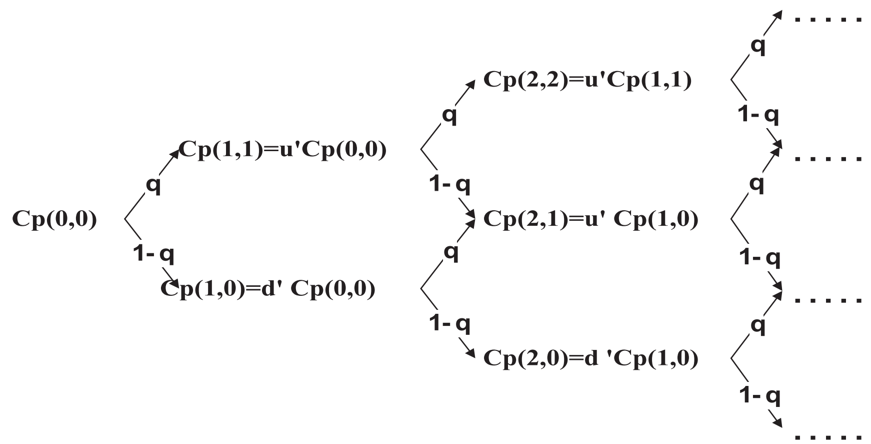

Fig. 2. Binomial lattice stochastic process of carbon price.

curve hypothesis. Lee and Shih [1] proposed, besides accumulated production or installed capacity, accumulated premium expenditure also leads to cost reduction. Hence, the model that is referred to as the "two-factor" cost efficiency curve which not only captures the effect of learning by doing but also considers learning by searching, and this represents the relationship between technological advancement and accumulated premium expenditure. So this paper builds two-factor learning curve model as follows:

$$C_t = C_0 X_t^{-a} \mathrm{KS}_t^{-w}$$

$$\mathrm{LDR} = 1 - 2^{-a}$$

$$\mathrm{LSR} = 1 - 2^{-w}$$

$$X_t = Q_t + X_{t-1}$$

where X_t is the cumulative installed capacity, Q_t is the new installed capacity per year, KS_t is the cumulative R&D inputs, C_t is the cost/kWh for renewable energy power generation in the year t, C_0 is the cost/kWh for the renewable energy power generation in the base year, a is the elastic coefficient of learning-by-doing, w is the elastic coefficient of learning-by-searching, LDR is the technology learning rate of learning-by-doing, LSR is the technology learning rate of learning-by-searching.

This paper assumes that technology learning rate of learning-by-doing and technology learning rate of learning-by-searching are constant during planning periods. Hence, we can get the deformation of original model by which we can get the unit cost in the planning periods.

$$\left\{ \begin{array}{l} C_t = C_0 X_t^{-a} \mathrm{KS}_t^{-w} \\ C_{t-1} = C_0 X_{t-1}^{-a} \mathrm{KS}_{t-1}^{-w} \end{array} \right\} \quad C_t = C_{t-1} (X_t / X_{t-1})^{-a} (\mathrm{KS}_t / \mathrm{KS}_{t-1})^{-w}. \tag{1}$$

3.1.4. Subsidy for renewable energy

The development of renewable energy is inseparable from the supports of policies. Currently, China has established renewable energy development policy system which is composed of law, supportive policy, and development plan. These policies complement each other and provide a good environment for the development of renewable energy. These supportive policies include tax relief, FIT, and subsidized loans of which price subsidy is the core. According to current policy for renewable energy in China, we can get the price subsidy

$$R_g = \mathrm{FIT}_r - P_d \tag{2}$$

where R_g is the unit price subsidy, FIT_r is the renewable energy feed-in tariff, P_d is the desulfurization electricity price.

It is different from the previous studies [1–3] where subsidy/kWh is equal to FIT_r minus the unit cost of power generation.

3.2. Real option model

After taking the factors mentioned above into account, we establish the policy evaluation model based on real option to evaluate the price subsidy under current development plan of renewable energy.

3.2.1. Governmental perspective

Here what we consider is the stage of formulating development goals. Government is concern with whether the new development goal can be achieved in the remaining planning periods. We think the value of developing renewable energy is not just the economic value but one kind of comprehensive value including resource value, environmental value, and economic value. The resource value is represented by reduced fossil energy consumption. The environmental value is represented by reduced carbon mitigation cost. At the same time, we assume CDM is effective and use carbon price to reflect the unit economic value. For simplicity, we just consider the unit decision value which is reflection of income and expenditure in the whole lifetime. The main idea here is that decision value is revenue minus cost which is similar with previous studies [1–3].

Fig. 3 presents the random decision-making process of developing renewable energy. At each node, NRE cost increase with probability p or drops with probability $1-p$, carbon price increase with probability q or drops with probability $1-q$. So there are four cases in the next node. Binomial is expanded to quadrinomial. This method is same as the model used by Fan et al. [54] who called it bidimensional binominal lattices approach. But we did not consider the correlation between random factors. In order to compare the result of NPV and ROA, we first provide the function of unit decision value at each decision nodes using NPV as follows:

$$V(t,\ i,\ j) = S(t,\ i) + \mathrm{Cp}(t,\ j) + \mathrm{CC}_m - C_t - aR_g \quad 0 \le i,\ j \le t \le T \tag{3}$$

where $V(t,i,j)$ is the unit decision value for government, $S(t,\ i)$ is the NRE cost with t periods elapsed and i upward cost movement, $\mathrm{Cp}(t,\ j)$ is the carbon price with t periods elapsed and j upward cost movement, CC_m is the saved carbon mitigation cost, C_t is the cost/kWh for renewable energy power generation in the year t, aR_g is the unit price subsidy, a is the subsidy rate, T is the number of time periods.

However, due to the flexibility of investment strategy, real option is better suited to policy evaluation of renewable energy. Government has two choices at each decision point, i.e., continue or abandon developing renewable energy. Support developing

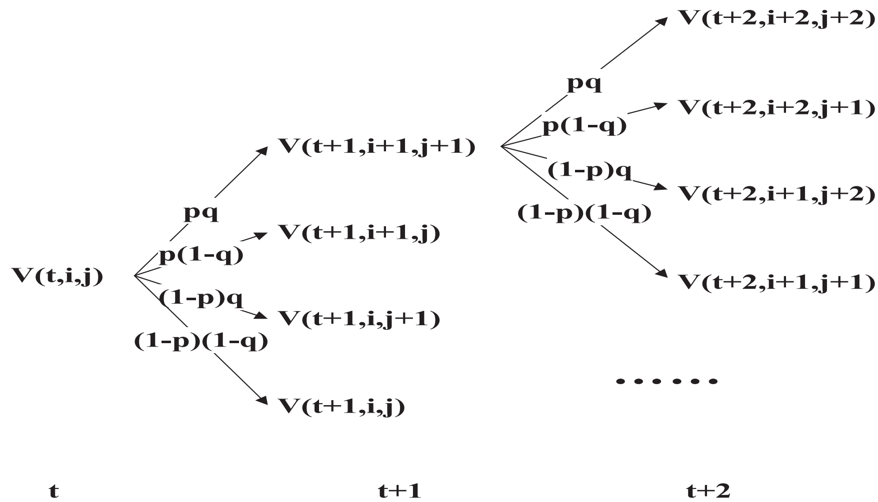

Fig. 3. Stochastic decision-making process of developing renewable energy.

renewable energy when unit decision value is greater than zero, and abandon developing renewable energy when unit decision value is less than zero. The unit decision value will be zero for decision maker when developing renewable energy power generation will be abandoned. The model in our paper is different from previous studies'. First, the previous model considers CO_2 emission cost which is constant. But this study consider carbon mitigation cost and carbon price. The carbon mitigation cost is different from carbon price. The carbon mitigation cost is the saved opportunity cost and the carbon price represents the unit revenue of CDM. Second, the method previous study used is European option, while the method in our study is American option. By European option, we can get the initial value of the planning period. But through American option, the result is the annual value. Third, the model in this study is more complex. Binomial is expanded to quadrinomial. Fourth, the study not only considers the unit decision value but also analyses the save-path rate. Fifth, this study is more suitable for the actual situation of China.

The value in general binominal lattice can be estimated using backward-induction. In this study, $S(t,\ i)$and $\mathrm{Cp}(t,\ j)$ are uncertain factors. C_t changes with time. aR_g and CC_m are constant. So we cannot resolve it directly. Indirect conversion is needed. According to backward-induction, we should resolve $W(t,\ i,\ j)=S(t,\ i)+\mathrm{Cp}(t,\ j)+\mathrm{CC}_m-aR_g$ firstly. And we resolve $V(t,\ i,\ j)=W(t,\ i,\ j)\ -C_t$ afterwards.

In accordance with the above ideas, the government must decide whether or not to support invest and have no right to delay at the last year of the planning time ($t=T$). So the unit value of developing renewable energy is as follows:

$$V(t,\ i,\ j)=\ \max\{\mathrm{S(t,\ i)+Cp(t,\ j)+CC_m-aR_g-C_t},0\}\quad 0\le i,\ j\le t \tag{4}$$

Generally, for$\forall 0<t<T$

$$\begin{aligned}W(t,\ i,\ j)=\ \max\{&e^{-r(T/n)}\{p[qW(t+1,\ i+1,\ j+1)\\&+(1-q)W(t+1,\ i+1,\ j)].\quad +(1-p)[qW(t+1,\ i,\ j+1)\\&+(1-q)W(t+1,\ i,\ j)]\},S(t,\ i)+\mathrm{Cp}(t,\ j)+\mathrm{CC}_m-aR_g\}\end{aligned}$$

The unit value of developing renewable energy is

$$V(t,\ i,\ j)=\ \max\{W(t,\ i,\ j)-C_t,\ 0\}\quad 0\le i,\ j\le t \tag{5}$$

Based on the above, we can get the unit decision value at each node and the save-path rate every year during the planning periods for government.

3.2.2. *Investor's perspective*

Investor is the policy observer. Government as the policy maker should consider the benefit of investors. For the majority of investors, they will compare renewable energy and NRE power generation in order to determine relative economy and decide whether and when to invest. The profit from CDM is one part of the investors' benefit. For renewable energy project investment, they have no need to reduce carbon emission. So we do not consider the saved carbon mitigation cost of developing renewable energy. Therefore, the decision of investors is affected by the NRE cost, carbon price, subsidy, and renewable energy cost. The function of unit decision value based on NPV is as follows:

$$V(t,\ i,\ j)=S(t,\ i)+\mathrm{Cp}(t,\ j)+aR_g-C_t\quad 0\le i,\ j\le t\le T \tag{6}$$

where $V(t,i,j)$ is the unit decision value for investors, C_t is the cost/kWh for renewable energy power generation in the year t, aR_g is the unit price subsidy, a is the subsidy rate, T is the number of time periods.

For the real option method, we can also use backward-induction to resolve the model, $S(t,i)$ and $\mathrm{Cp}(t,\ j)$ are uncertain factors. C_t changes with time. aR_g is constant. We can solve it step by step. We should resolve $W(t,\ i,\ j)=S(t,\ i)+\mathrm{Cp}(t,\ j)-aR_g$ using backward-induction firstly, and then solve $V(t,\ i,\ j)=W(t,\ i,\ j)-C_t$.

At the last year of planning period ($t=T$), the investors must decide whether or not to invest and have no right to delay investment. So the unit decision value of developing renewable energy is

$$V(t,\ i,\ j)=\ \max\{S(t,\ i)+\mathrm{Cp}(t,\ j)+aR_g-C_t,\ 0\}\quad 0\le i,\ j\le t \tag{7}$$

Generally, for$\forall 0<t<T$

$$\begin{aligned}W(t,\ i,\ j)=\ \max\{&e^{-r(T/n)}\{p[qW(t+1,\ i+1,\ j+1)\\&+(1-q)W(t+1,\ i+1,\ j)].\quad +(1-p)[qW(t+1,\ i,\ j+1)\\&+(1-q)W(t+1,\ i,\ j)]\},S(t,\ i)+Cp(t,\ j)+aR_g\}\end{aligned}$$

The unit decision value of developing renewable energy is

$$V(t,\ i,\ j)=\ \max[W(t,\ i,\ j)-C_t,\ 0]\quad 0\le i,\ j\le t \tag{8}$$

Through this process, the unit decision value at each node and the save-path rate in every year for investors can be obtained.

4. Parameter estimation and scenario analysis

The data on solar PV power generation in China is empirically analyzed. China is rich in solar energy resource. Solar PV is the

most widely used solar power generation technology. On the whole, there is certain gap between China and the developed countries in the scale and technology level of solar PV power generation. In addition, after trade friction between China and Europe, the State Council issued the Opinions on Promoting the Healthy Development of the PV Industry and proposed the installed capacity of solar PV power generation reach 35,000 MW and above by 2015. Therefore, expanding the domestic solar PV power generation is particularly urgent and important. This section constructs base case and the case of changing subsidy rate to study the effect of price subsidy on government and investors under the development plan of solar PV power generation. Whether the government and investors could achieve balance of interest is also examined. Table 1 presents the data used in the study.

4.1. Parameter estimation

(1) Non-renewable energy cost: As coal-fired generation dominates China's thermal power generation, this paper takes the average cost of coal-fired power to represent NRE cost. It is known that the proportion of coal in NRE cost is about 0.8. So we can get the initial NRE cost according to the following equation: $S(0,0)=P_{coal}(3.33\times10^{-4})/80\%$ (P_{coal}: coal price, yuan/t; the unit of NRE cost is yuan/kWh). We use the price of Bohai rim steam coal to represent Chinese coal price. The data is from Qinhuangdao coal net. Through calculating with historical data of coal price and the method mentioned in footnote 1, we can get $\sigma=0.05009$, $p=0.95$, $u=1.05$. We put the average coal price of the 48 weeks in 2012 as the initial coal price in early 2013. After calculation, the initial value of NRE cost can be obtained: $S(0,0)=0.29$ yuan/kWh. Fig. 4 shows the binomial lattice stochastic process of NRE cost with actual data.

(2) Carbon price: This study assumes that the CDM is effective. The data in this study is from the European carbon emissions market. Due to the limited data as well as the abnormal decline of carbon price in later period, the sample interval is taken from October of 2009 to February of 2012. Through calculating with the historical data of carbon price and the method mentioned in footnote 1, we can obtain $\sigma'=0.36$, $q'=0.49$, $u'=1.43$. The average emission coefficient of the thermal power plant in China is 0.9984 kg/kWh. The initial carbon price in early 2013 is equal to the average price of the 12 months in 2012. So the initial price of carbon is 0.12 yuan/kWh. Fig. 5 presents the binomial lattice stochastic process of carbon price with actual data.

(3) Renewable energy cost: C_t could be obtained by dividing the total cost in the whole lifetime to each kWh. The total cost contains initial investment expenditure, operation and maintenance cost as well as tax. Due to the decline of PV module, the cost of solar PV power generation/kWh (C_t) has down to 0.9 yuan/kWh in 2013. We get these parameters from published data of Chinese Renewable Energy Industry Association. In addition, considering China's actual situation and some previous study [55], we set the rate of learning-by-doing and learning-by-searching to 17.5% and 10% respectively. The rate of annual cumulative R&D inputs is equal to the rate of cumulative premium of solar photovoltaic power generation. This idea is similar with the study of Lee and Shih [1]. And the installed capacity every year are obtained from the plan posed by the opinions of state council on promoting the healthy development of the photovoltaic industry and the 12th Five-year Plan of Chinese renewable energy. Therefore, employing

Table 1
Input parameters for scenario analysis.

Variable	Description	Initial value	Notes
$S(t,\ i)$	NRE cost	0.29 yuan/kWh	$S(0,\ 0)=P_{coal}(3.33\times10^{-4})/80\%$. Data from Qinhuangdao coal net.
$Cp(t,\ j)$	Carbon price	0.12 yuan/kWh	Data from Europe's carbon trading market.
C_t	Cost/kWh for solar PV power generation in the year t.	0.9 yuan/kWh	C_t could be obtained by formula (1). We get the value of C_t in the base year of the planning periods from published data of Chinese Renewable Energy Industry Association.
CC_m	Carbon mitigation cost	0.23 yuan/kWh	Data from some public information from National Development and Reform Commission of China.
Q_t	New installed capacity/year of solar PV power generation		Data from the 12th Five-year Plan of Chinese renewable energy and the options of Sate Council on promoting healthy development of the PV industry.
R_g	Unit price subsidy	0.54 yuan/kWh	Calculate with $R_g=\mathrm{FIT}_r-P_d$. Data from the related policies about FIT_r and P_d.
a	Subsidy rate	1	
P_d	Desulfurization electricity price	0.46 yuan/kWh	It is one kind of average price in China which is calculated based on related policy and regulation about P_d in different regions.
FIT_r	Feed-in tariff	1	It is one kind of unified price in China based on related policies and regulations.
T	Number of time periods	8	2013–2020, which is the target year of the medium and long-term development plan for RE in China set up in 2007.
n	Number of volatility periods	8	
σ	Volatility rate of NRE cost	0.05	Calculate with historical data of the coal price and method which is explained in footnote 1.
u	Range of NRE cost upward movement	1.05	$u=e^{\sigma\sqrt{T/n}}$
d	Range of NRE cost downward movement	0.95	$d=1/u$
p	Probability of a NRE cost increase	0.95	$p=(e^{r(T/n)}-d)/(u-d)$
σ'	Volatility rate of carbon price	0.36	Calculate with historical data of the carbon price and the method which is explained in footnote 1.
u'	Range of carbon price upward movement	1.43	$u'=e^{\sigma'\sqrt{T/n}}$
d'	Range of carbon price downward movement	0.7	$d'=1/u'$
q	Probability of a carbon price increase	0.49	$q=(e^{r(T/n)}-d')/(u'-d')$
LDR	Learning-by-doing rate	17.5%	Data from related literature [55].
LSR	Learning-by-researching rate	10%	Data from related literature [55].
r	Risk-free interest rate	4.76%	Average one-year fixed deposit rates of People's Bank of China, 1991–2012

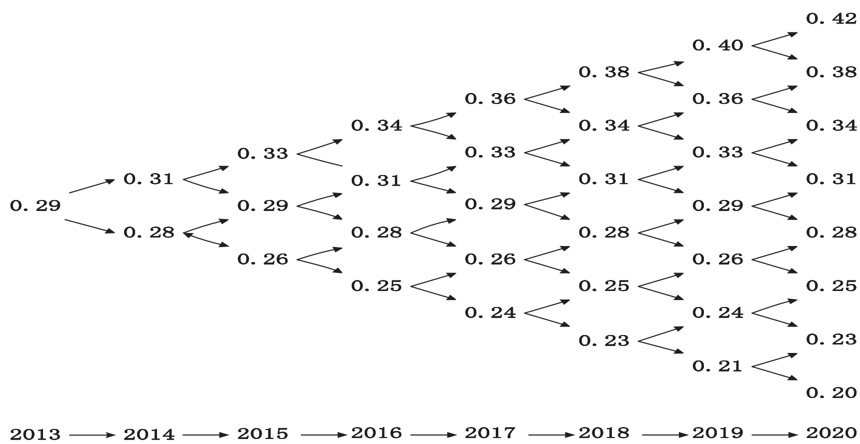

Fig. 4. Binomial lattice stochastic process of NRE cost with actual data (yuan/kWh).

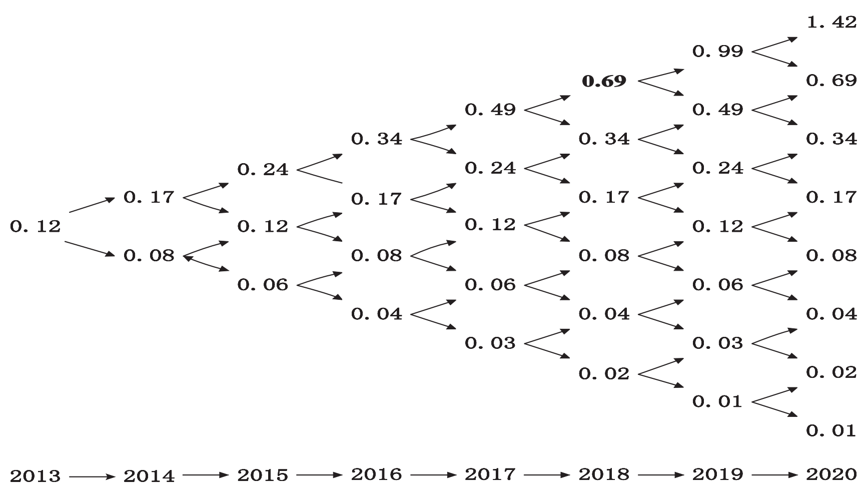

Fig. 5. Binomial lattice stochastic process of carbon price with actual data (yuan/kWh).

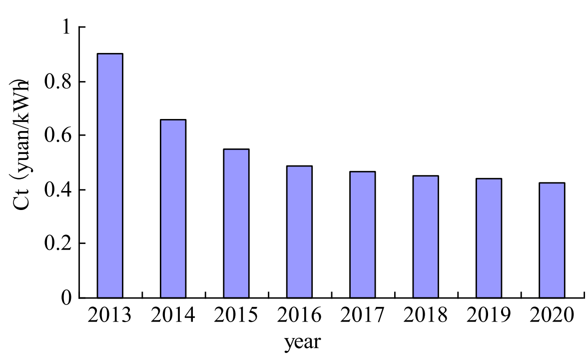

Fig. 6. Cost/kWh of power produced by solar PV (yuan/kWh).

formula (1), we can get the cost/kWh in the planning periods which is shown in Fig. 6.

Table 2
The government's unit decision value of developing solar generation using NPV (yuan).

2013	2014	2015	2016	2017	2018	2019	2020
−0.57	−0.49	−0.3	−0.11	0.07	0.31	0.65	1.11
	−0.58	−0.42	−0.29	−0.18	−0.04	0.14	0.38
	−0.52	−0.48	−0.37	−0.3	−0.22	−0.11	0.03
	−0.61	−0.33	−0.41	−0.36	−0.30	−0.23	−0.15
		−0.45	−0.15	−0.39	−0.34	−0.29	−0.23
		−0.51	−0.32	0.03	−0.36	−0.32	−0.27
		−0.36	−0.40	−0.21	0.27	−0.33	−0.29
		−0.48	−0.45	−0.34	−0.08	0.60	−0.30
		−0.54	−0.18	−0.4	−0.25	0.1	1.06
			−0.35	−0.42	−0.34	−0.15	0.34
			−0.44	0.0008	−0.38	−0.27	−0.02
			−0.48	−0.25	−0.40	−0.33	−0.19
			−0.20	−0.37	0.24	−0.36	−0.27
			−0.38	−0.43	−0.11	−0.37	−0.32
			−0.46	−0.46	−0.29	0.57	−0.34
			−0.50	−0.03	−0.37	0.06	−0.35
				–	–	–	–
				–	–	–	–

4.2. Scenario analysis

4.2.1. Base case analysis

The purpose of base case analysis is to analyze the effect of subsidy on government and investors under current situation. At first, we analyze the decision value and save-path rate from the perspective of government. Table 2 shows the unit decision value of developing solar PV power generation assessed by calculating the NPV. The NPV in early 2013 is −0.57. The NPV in 2013 to 2016 are also less than zero. These reflect the government should suffer

Table 3
The government's unit decision value of developing solar generation using ROA (yuan).

2013	2014	2015	2016	2017	2018	2019	2020
0	0	0	0	0.13	0.37	0.66	1.11
	0	0	0	0	0.0003	0.15	0.38
	0	0	0	0	0	0	0.03
	0	0	0	0	0	0	0
		0	0	0	0	0	0
		0	0	0.09	0	0	0
		0	0	0	0.33	0	0
		0	0	0	0	0.62	0
		0	0	0	0	0.11	1.06
			0	0	0	0	0.34
			0	0.06	0	0	0
			0	0	0	0	0
			0	0	0.29	0	0
			0	0	0	0	0
			0	0	0	0.58	0
			0	0.03	0	0.08	0
				–	–	–	–
				–	–	–	–

Table 4
The investors' unit decision value of developing solar generation based on NPV (yuan).

2013	2014	2015	2016	2017	2018	2019	2020
0.05	0.36	0.55	0.74	0.92	1.16	1.5	2
	0.27	0.43	0.56	0.67	0.81	0.99	1.23
	0.33	0.37	0.48	0.55	0.63	0.74	0.88
	0.24	0.52	0.44	0.49	0.55	0.62	0.70
		0.4	0.70	0.46	0.51	0.56	0.62
		0.34	0.53	0.88	0.49	0.53	0.58
		0.49	0.45	0.64	1.12	0.52	0.56
		0.37	0.40	0.51	0.77	1.45	0.55
		0.31	0.67	0.45	0.6	0.95	1.91
			0.5	0.43	0.51	0.70	1.19
			0.41	0.85	0.47	0.58	0.83
			0.37	0.60	0.45	0.52	0.66
			0.65	0.48	1.09	0.49	0.58
			0.47	0.42	0.74	0.48	0.53
			0.39	0.39	0.56	1.42	0.51
			0.35	0.82	0.48	0.91	0.50
				–	–	–	–
				–	–	–	–

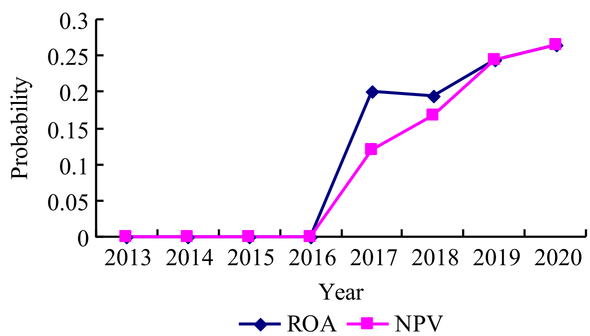

Fig. 7. The curve of save-path rate based on ROA and NPV for government.

loss during this time. Then according to the ROA (Table 3), the unit decision value of developing solar generation is zero at any node from 2013 to 2016. These also reflect the government is unprofitable and the result is similar with the value calculated with NPV. After 2018, there appear some decision points where unit decision value is more than zero. But the save-path rate is very low (The save-path rate can be obtained by dividing the number of decision point where unit decision value is more than zero by the number of all decision point in one year.). These suggest the risk of suffering loss is greater than the likelihood of obtaining benefit during this period (This paper assumes 0.5 is the risk control line. That save-path rate is greater than 0.5 means the probability of benefit is greater that the risk of suffering loss.). It can be seen from Fig. 7 that the save-path rate calculated with ROA is more than the value using NPV. Hence the managerial flexibility and the unit decision value are underestimated using NPV. But the difference is very small. It is because volatility rate of NRE cost and carbon price is relatively small, and the speed of technology progress is not fast enough. In brief, under current level of subsidy, if Chinese government wants to develop solar PV power generation, the government will suffer loss. So it is not optimal time to develop solar PV power generation.

For investors, comparing Tables 4 and 5, we can see the unit decision value in some decision node calculated by ROA is greater than that using NPV. So ROA can capture the value of flexibility which the NPV neglected. The gap between them is not very big. The reason is also that volatility rate of NRE cost and carbon price is relatively small, and the speed of technology progress is not fast

Table 5
The investors' unit decision value of developing solar generation based on ROA (yuan).

2013	2014	2015	2016	2017	2018	2019	2020
0.05	0.36	0.55	0.74	0.92	1.19	1.5	1.96
	0.27	0.43	0.56	0.67	0.82	0.99	1.23
	0.33	0.37	0.48	0.55	0.64	0.74	0.88
	0.24	0.52	0.44	0.49	0.55	0.62	0.70
		0.4	0.70	0.46	0.51	0.56	0.62
		0.34	0.53	0.88	0.49	0.53	0.58
		0.49	0.45	0.64	1.15	0.52	0.56
		0.37	0.40	0.51	0.78	1.45	0.55
		0.31	0.67	0.45	0.6	0.95	1.91
			0.5	0.43	0.51	0.70	1.19
			0.41	0.85	0.47	0.58	0.83
			0.37	0.60	0.45	0.52	0.66
			0.65	0.48	1.11	0.49	0.58
			0.47	0.42	0.74	0.48	0.53
			0.39	0.39	0.56	1.42	0.51
			0.35	0.82	0.48	0.91	0.50
				.	.	.	.
				.	.	.	.

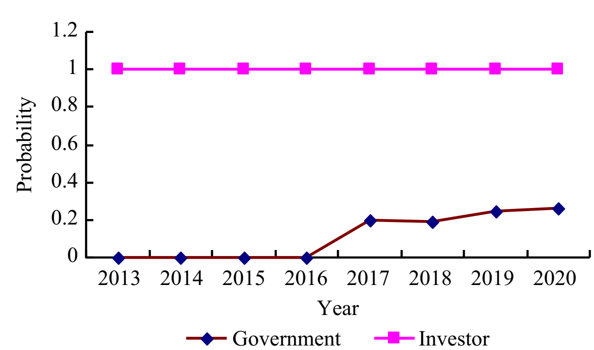

Fig. 8. The curve of save-path rate for government and investors based on ROA.

enough. On the other hand, it is can be seen from Table 5 that the initial unit decision value is 0.05 that is just greater than 0. This indicates the subsidy level is reasonable. The investor could benefit from the development of solar PV power generation. And

the government does not bear additional financial burden. In the following years, the save-path rate is 100% and the unit decision value is gradually rising. It implies that government should reduce the subsidy timely according to the rising of unit decision value.

In addition, Fig. 8 shows the curve of save-path rate for government and investors based on ROA. We can see there is no intersection between these two curves. So government and investor cannot achieve the balance of interest (The balance point of interest is one case that the save-path rate of government and investors are all greater than 0.5.). This indicates although we consider the comprehensive value and flexibility value of developing solar PV power generation in here, government would also suffer loss. This also explains the reason that government levy renewable energy surcharge to alleviate the loss.

4.2.2. Varying the subsidy rate

To measure the dynamic changes of save-path rate for government and investors resulted from the changes of subsidy rate. We further set the subsidy rate to different numerical values (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1). Figs. 9 and 10 show the results.

Fig. 9 shows the change of save-path rate for government. We can see when the subsidy rate is above the 0.4 ($a>0.4$), the save-path rate in any year of the planning period cannot rise above 0.5. That is to say the government would suffer loss at this level of subsidy. When the subsidy rate is reduced to 0.4 ($a=0.4$), the save-path rate will rise to 0.53 in 2019. When the subsidy rate is reduced to 0.3 ($a=0.3$), the save-path rate will rise to 0.56 in 2016. When the subsidy rate is reduced to 0.2 ($a=0.2$), the save- path rate will rise to 0.69 in 2016. When the subsidy rate is reduced to 0.1 ($a=0.1$), the save-path rate will rise to 0.78 in 2015. When the subsidy rate is 0, the save-path rate will be 0.5 in 2014. It is obvious that the save-path rate could rise above the 0.5. It is to say government could benefit during the planning period when considering the comprehensive value and flexibility value of developing renewable energy. Reducing subsidy could ease the loss of government. However, excessive reduction of subsidy is bad for the promotion of renewable energy investment. So the urgent

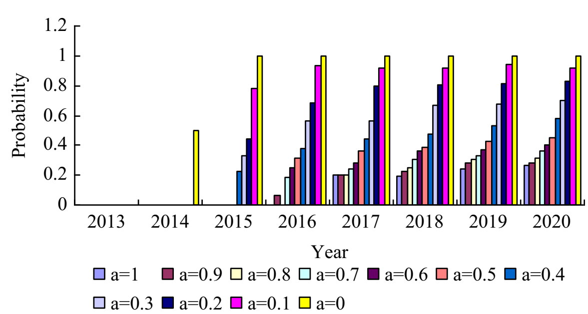

Fig. 9. The change of save-path rate for government.

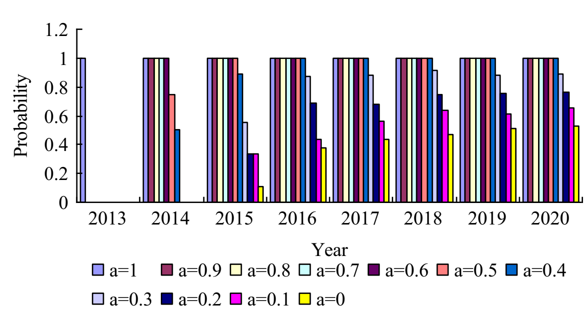

Fig. 10. The change of save-path rate for investors.

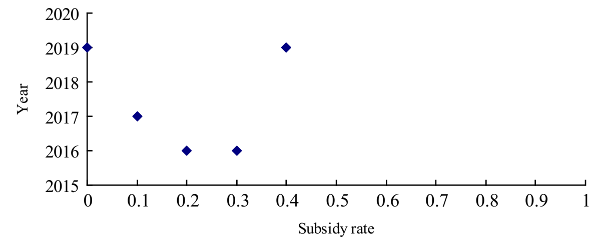

Fig. 11. The year of achieving balance of interest under different subsidy rates.

priority for government is to reduce the cost of solar power generation. Only by this government can reverse the situation of loss as soon as possible.

Fig. 10 shows the change of save-path rate under different subsidy rates from the perspective of investors. When the subsidy rate is 0, the save-path rate from 2013 to 2018 is zero and the save-path rate after 2018 is around 0.5. Therefore, the development of solar PV power generation cannot survive without the support of subsidy currently. With the increase of subsidy rate, more and more save-path rates become greater than 0.5. So government should reduce subsidy gradually. The lowest ratio of save path should no less than 0.5. But what is the most appropriate subsidy rate depends on the investor's attitude towards risk and the ability to bear risk. This indicates that government should not only develop appropriate level of subsidy but also strengthen the promotion and improve the citizens' awareness of renewable energy utilization.

Given above, we further attempt to find the balance point of interest. Fig. 11 shows the year of achieving balance of interests under different subsidy rate. When the subsidy rate is 0.4 ($a=0.4$) and 0 ($a=0$), both government and investors could benefit in 2019. If the subsidy rate is set to 0.2 or 0.3 ($a=0.2$, 0.3), both government and investors could benefit in 2016. If the subsidy rate is 0.1 ($a=0.1$), both government and investors could benefit in 2017. On the other hand, the curve of interest equilibrium point is U curve. This is because the subsidy should consider the benefit of government and investors, and hence subsidy rate cannot be too high or too low. The exact level of subsidy is decided by the investors' risk consciousness and national development goal for renewable energy. This indicates one kind of methods determining the level of subsidy. Because what we considered is comprehensive value of developing renewable energy. So the results may seem to be a little different from the reality.

5. Conclusions

This paper establishes a policy evaluation model using American option and the learning curve methods from the perspective of government and investor respectively. The change of NRE cost, carbon price, renewable energy cost, and price subsidy are all considered in this model. According to the proposed model, we analyze the unit decision value and save-path rate of developing renewable energy during the planning period. The existence of balance point of interest is also examined.

The solar PV power generation in China as the empirical study is analyzed. The results are obtained by base case analysis and sensitivity analysis of subsidy rate. At first, under current level of subsidy, the government inevitably suffer loss if develop solar PV power generation during planning period. For investors, the unit decision value at all decision nodes is just over zero and the save-path rate during the planning period are all 100%. So the subsidy is reasonable. The unit decision value is gradually rising with the passage of time. Government should reduce the subsidy timely

according to the change of unit decision value. In addition, government and investors cannot find the balance point of interest under current level of subsidy. Second, considering the reduction of subsidy rate, government could avoid loss or obtain a benefit. For investors, the unit decision is still rising and the number of save-path rate over 100% is increasing. So these further proved the subsidy should be decreased year by year. The most important is, in this case, the government and investors could achieve the balance of interest.

In contrast with the previous studies, this study considers the benefit of government and investors. The method in this paper is American option. So the decision maker could decide whether to continue to develop solar PV power generation every year. The factors in this model include the uncertain NRE cost, carbon price, renewable energy cost, and price subsidy. The model in this study is more complex. Binomial is expanded to quadrinomial. Both unit decision value and save-path rate are analyzed. This model could be used to policy evaluation of other renewable energies.

However, considering the complexities of renewable energy investment and policy evaluation, there are some limitations that should be pointed out. At first, this paper is the highest recapitulation of reality, and it is an ideal situation. So some results do not go quite as reality. Second, the data collected by published data of government and related literatures may influence the rationality of the analysis results. Third, there may be some other influencing factors that we have not considered. Finally, we have not take into account the benefit of the created technical advantage. The above remain to be made up in future studies. We think that resolving the above limitations will be a viable avenue for further research and model improvement. Despite the above limitations, we think this paper also has a certain reference value.

Acknowledgments

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